

## APPENDIX A

### VIIRS USER'S GUIDE – MANUAL ANALYSIS OF VIIRS IMAGERY

#### A.1. INTRODUCTION

The current DMSP OLS and TIROS AVHRR sensors have limited spectral content compared to the VIIRS sensor designed by Raytheon. While MODIS will provide the research community with a significantly enhanced capability, the operational community will not fully realize the value of these data until the launch of the NPOESS VIIRS sensor. In the interim, research scientists will continue to improve the algorithm technology and MODIS-derived environmental data products (EDRs). Thus, it becomes essential that the algorithm technology and user knowledge be brought forward together to fully realize the value of true multispectral VIIRS measurements. The Raytheon VIIRS User's Guide is recommended as THE vehicle to convey VIIRS algorithm technology to the operational user community.

Raytheon's goal in preparing this appendix is to begin the documentation process necessary for creating a VIIRS User's Guide. Our ultimate goal is to publish a manual that (1) examines the theoretical basis for feature identification in VIIRS imagery and (2) provides users of VIIRS data with the knowledge needed to fully utilize these data to address their unique mission requirements. In addition, Raytheon plans to routinely conduct training sessions in a classroom environment to users of NPOESS VIIRS data.

#### A.2. THEORETICAL BASIS FOR FEATURE IDENTIFICATION

As noted in Section 3.4.3.1 of the VIIRS Imagery ATBD, the ability to manually identify clouds in multispectral imagery is based upon the capability of the VIIRS imagery to maximize the contrast between the cloud and its cloud-free (surrounding) environment. More precisely:

$$C = I_v(0)_{\text{cloud}} / I_v(0)_{\text{background}} \quad (\text{A-1})$$

The satellite observed radiance,  $I_v(0)$ , may be composed of (1) reflected solar radiation, (2) thermal radiation emitted by terrestrial features, or (3) both when observations are made in the 3-5 mm wavelength region. However, for cloud-free conditions, the monochromatic, terrestrial radiation is described by Equation A-2:

$$I_v(0) = \varepsilon_v B_v[T_s] + \int_{p_s}^0 B_v[T(p)] \frac{f T_v(p)}{f p} dp + (1 - \varepsilon_v) \int_0^{p_s} B_v[T(p)] \frac{f T_v(p)}{f p} dp \quad (\text{A-2})$$

where:

- $v$  = wavenumber of emission
- $B_v[T(p)]$  = Planck function at wavenumber ( $v$ ) for temperature ( $T$ )
- $\varepsilon_v$  = emissivity of surface at wavenumber ( $v$ )

|            |  |
|------------|--|
| $T_v(p_s)$ | = atmospheric transmittance between pressure level ( $p_s$ ) and space |
| $I_v(0)$   | = monochromatic radiance arriving at satellite.                        |
| $p_s$      | = surface pressure   |
| $T_s$      | = surface temperature  |

For imaging sensors, the atmospheric transmittance between pressure levels and space is very small and Equation (A-2) is closely approximated by Equation (A-3), which shows that the radiance arriving at the satellite sensor is a function of the emissivity of the surface, the surface temperature, and the transmission from the surface to the sensor:

$$I_v(0) = \epsilon_v B_v [T_s] T_v(p_s) \quad (\text{A-3})$$

Therefore, the real goal of the Raytheon VIIRS User's Guide is to provide the meteorological satellite analyst with the knowledge base to fully exploit differences between feature emissivity, feature temperature, and/or atmospheric attenuation of features in multispectral imagery in order to positively identify each feature in the VIIRS data set.

In addition to spectral signatures, some features are unique identified by spatial, textural, and thermal signatures. For example, cirrocumulus associated with strong vertical motions near the core of the jet stream may be uniquely identified by its fishbone effect when these clouds appear much like the skeleton of a fish. In addition, wind speed, direction, and the potential of severe turbulence may be assumed by the presence of wave (lenticular) clouds in the lee of a mountain range. Finally, clouds types are often distinguished only by their vertical location in the atmosphere, which can be determined from the cloud top temperature. Thus, using cloud top versus cloud-free surface temperatures of neighbor pixels is often adequate to differentiate low level water clouds (e.g. stratus) from middle-level water clouds (e.g. altostratus). Given additional information from other NPOESS sensors, such as rainfall occurrence from the microwave imagery, it becomes possible to differentiate between altostratus and nimbostratus solely from satellite data.

### A.3. VIIRS BAND SELECTION PROCESS

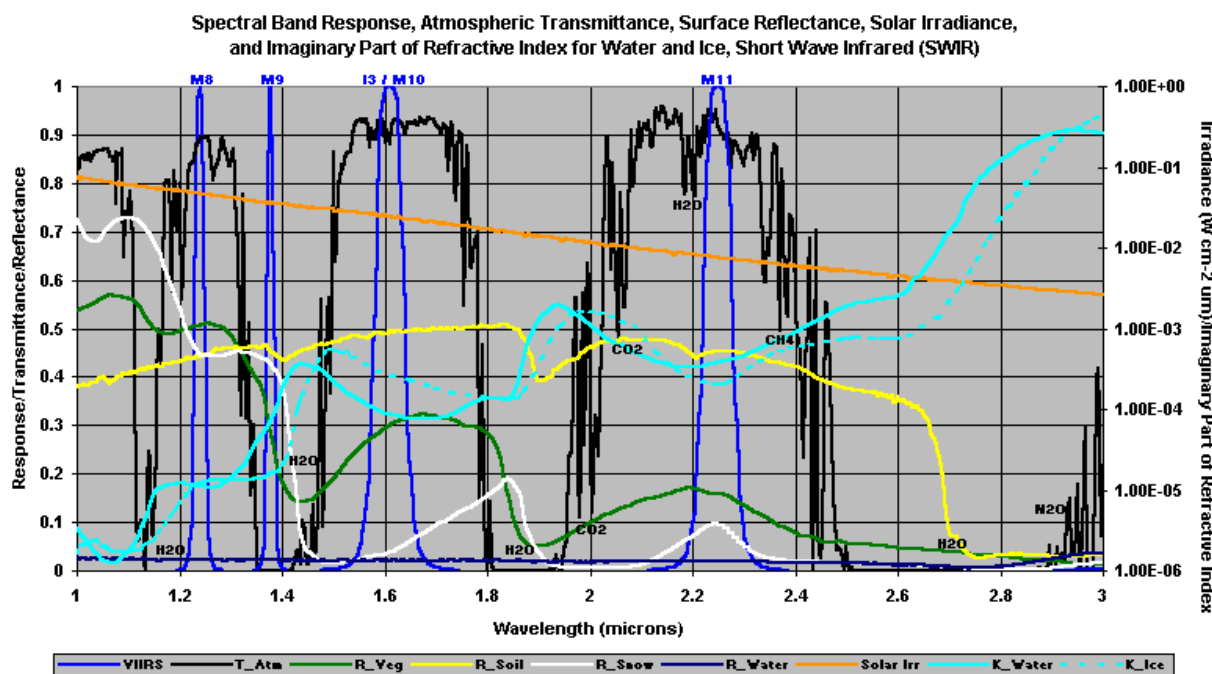
Bands selection for the Raytheon VIIRS sensor design is based upon the strength (strong and/or weak) of three components that make up the signatures of each feature. These components are: (a) surface radiance which includes temperature and emissivity or solar reflectivity, (b) cloud absorptivity or reflectivity, and atmospheric transmissivity. Examples of these features in several VIIRS channels are shown in Figure A-1.

The positive identification of clouds in multispectral imagery requires that the analyst understand and exploit the properties of water droplets and ice crystals, along with the spectral characteristics of different backgrounds in VIIRS imagery and imagery-assist bands. A discussion of the phenomenology associated with the features follows along with the definition

of bands selected to meet VIIRS threshold and objective requirements for the manually-generated cloud cover EDR, in Section 4.

#### A.4. PHENOMENOLOGY FOR SELECTION OF IMAGERY CHANNELS AND IMAGERY-ASSIST BANDS FOR MANUALLY-GENERATED CLOUD COVER EDR

The VIIRS SRD specifies that the spectral bandpasses required to meet the threshold requirements for the manually-generated cloud cover EDR and cloud type EDR must be at the "imagery" resolution. The flowdown of these requirements determined that only three spectral bands were required to meet the threshold requirements (Hutchison, 1998). However, the Raytheon Cloud and Imagery IPTs also demonstrated the use of imagery bands with imagery-assist data, collected at a more coarse resolution, to advance toward meeting objective requirements, especially for the cloud typing EDR. Therefore, this section begins with a discussion of the phenomenology associated with the selection of the VIIRS imagery channels in the Raytheon design. Subsequently, the phenomenology associated with non-imagery channels is presented for the bands that provide useful information for the manual detection of clouds and their classification by type.



**Figure A-1. Reflectivity, absorptivity, and transmissivity of atmosphere, surface and clouds in the Short-Wave Infrared (SWIR).**

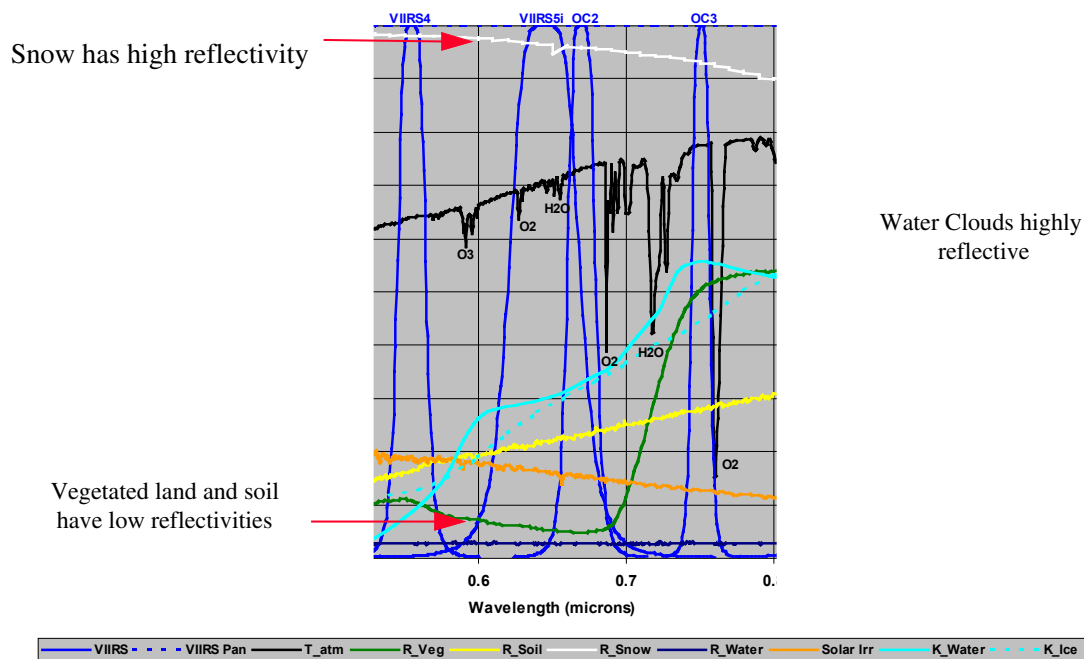
Figure A-1 shows the band positions for VIIRS channels M8, M9, I3/M10, and M11 (---) along with atmospheric transmissivity (---), reflectivity of vegetated (---) and bare soil (---) ice (white) and water surfaces (---), solar irradiance (gold), and imaginary components of the index of refraction for water (---) and ice (---).

### A.4.1. VIIRS Imagery Channels

The SRD states that "At a minimum, at least one daytime visible, one daytime/nighttime visible, and one IR channel shall meet the explicit imagery requirements." The Raytheon sensor design called for the identification of the least number of imagery channels required to satisfy minimum (threshold) requirements for manually-generated cloud data product EDRs. All other VIIRS channels would be collected at the lower (non-imagery) resolution.

#### A.4.1.1 Daytime Visible Imagery Channel

The Raytheon daytime visible imagery is centered at 0.645 microns. The justification for this selection is shown in Figure A-2.

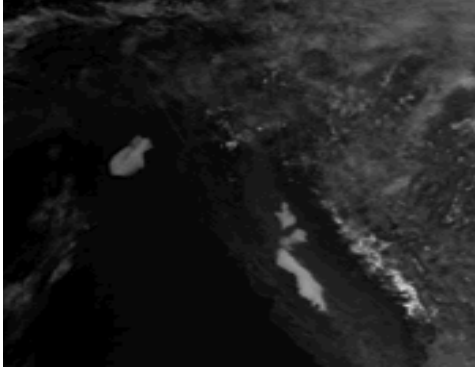


**Figure A-2. Phenomenology of the 645 nm band which is the daytime imagery channel of the Raytheon VIIRS design.**

Figure A-2 shows the location and spectral response function for the daytime visible band, along with the characteristics of the Earth-atmosphere system. The band is identified in the figure by its old designation (VIIRS 5i). It is clear that the reflectivity of vegetated land is very small in this band but it begins to increase quite rapidly at ~ 0.7 microns. By limiting the width of the band between 0.6-0.7 microns, we also avoid the water vapor absorption lines in the 0.7-0.8 micron region that could cause variations in cloud and land signatures. The reflectivity of water surfaces is even lower. On the other hand, the reflectivity of clouds is much larger which means this band is particularly valuable for discriminating between clouds and vegetated land and ocean surfaces.

Additionally, the reflectivity of snow is very high. Therefore, this channel is not good for differentiating between snow and clouds nor is it particularly useful for identifying boundaries between land and ocean surfaces.

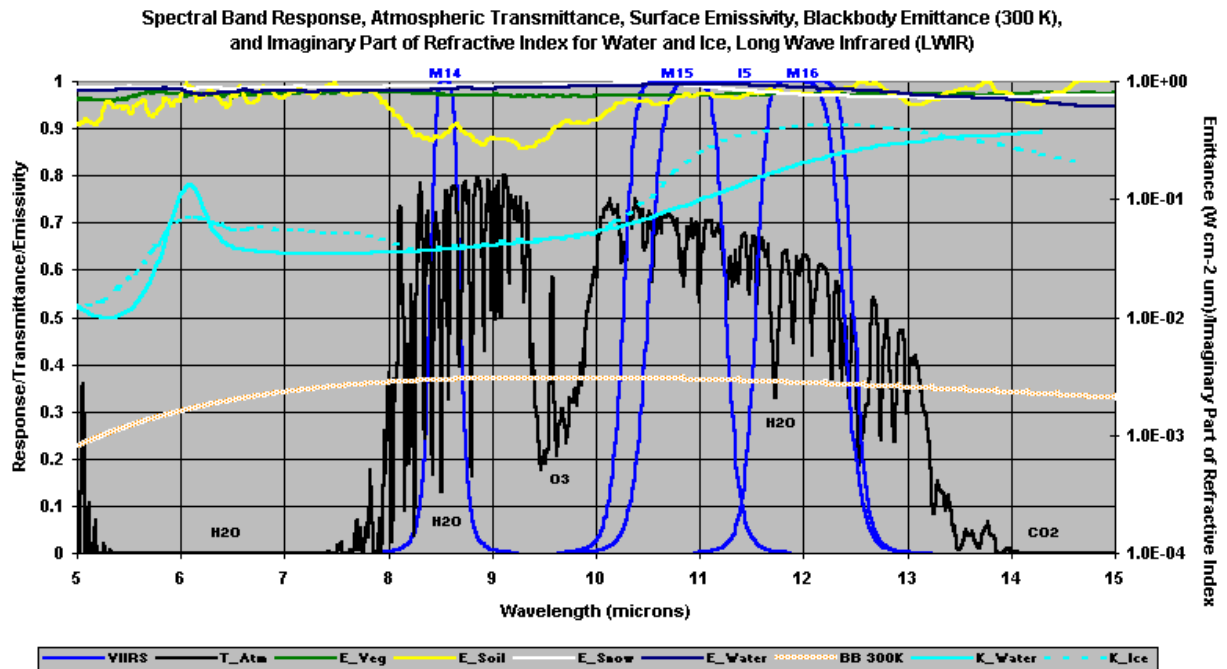
Examples of MODIS imagery collected in the narrow band will be included in future revisions of the document after EOS MODIS Terra data become available through the EOSDIS. Until that time, the AVHRR Channel 1 image in Figure A-3 is used to illustrate the features in this spectral band.



**Figure A-3. AVHRR Channel 1 Imagery.**

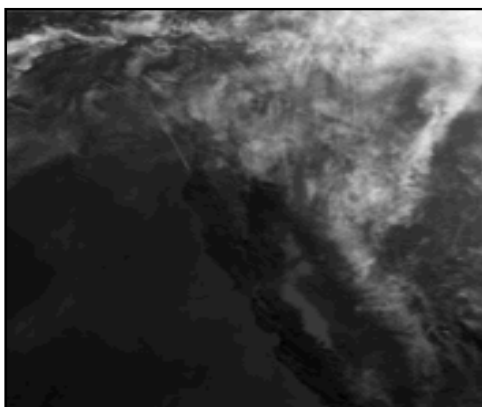
#### A.4.1.2. VIIRS Infrared Imagery Channel

Figure A-4 shows the location and spectral response function for the VIIRS infrared channel (I5) imagery along with the characteristics of the Earth-atmosphere system.



**Figure A-4. Phenomenology of the VIIRS Long-Wave Infrared (LWIR) Imagery band, centered at 11.45 microns, shows water vapor absorption across band.**

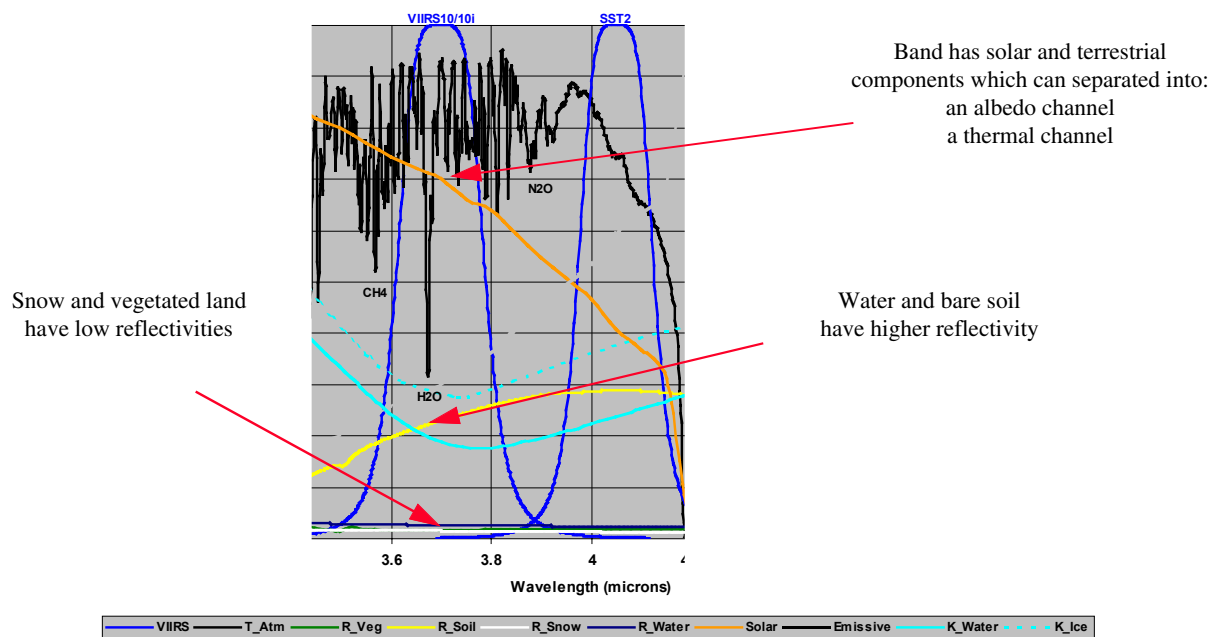
The VIIRS LWIR imagery channel is valuable for estimating the true radiating temperatures of objects in the band after correcting for atmospheric water vapor attenuation, which makes the measured cloud top temperature slightly colder than its true radiating temperature. In addition, due to the high absorptivity of ice at these wavelengths, thin cirrus is often easily detected in nighttime conditions, when other VIIRS data in the 1.378 micron band are not available. The AVHRR channel 5 imagery, shown in Figure A-5, shows the presence of thin cirrus in this bandpass.



**Figure A-5. AVHRR Channel 5 imagery**

#### A.4.1.3. VIIRS Mid-Wave Infrared Imagery Channel

In addition to the minimum required daytime visible and infrared imagery channels, the Raytheon design includes a mid-wavelength infrared imagery channel (band I4), centered near 3.7 microns, and shown in Figure A-6.



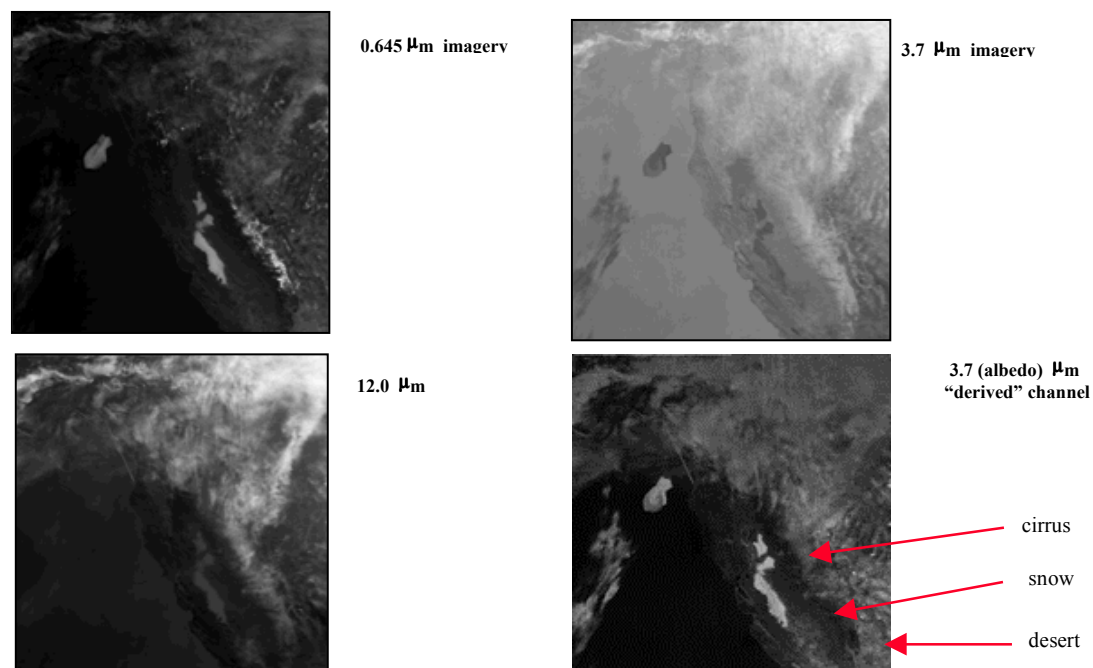
**Figure A-6. Phenomenology of the VIIRS Mid-Wave Infrared (MWIR) Imagery band, centered at 3.74 microns.**

Figure A-6 shows water vapor absorption lines in the VIIRS MWIR imagery channel (I4). The band is identified in the figure by its old designation (VIIRS 10i). The figure also shows that the reflectivity of snow is very low while that of clouds is much larger. It also shows that

considerable solar irradiance is present while the reflectivity of bare soil is relatively large compared to snow and clouds. Therefore, the 3.7 micron channel could be useful for differentiating between snow and clouds as well as clouds and vegetated land. However, distinction between cloud and bare soil appears difficult and the presence of terrestrial energy complicates the contrast between snow and clouds.

While the daytime 3.7 micron band imagery channel contains both solar and thermal energy, the capability has been demonstrated to separated this single channel into two channels and thus improve the discrimination between features in the spectral band. This process has been described in the literature (Hutchison et al., 1997) and utilizing the derived albedo channel allows significantly enhances the contrast between snow and water clouds. In fact the procedure also sufficiently enhances the contrast between snow and cirrus (ice) clouds so that snow can be observed through overcast cirrus cloudy conditions. Furthermore, the VIIRS flowdown process demonstrated that the thermal channel proves highly effective at differentiating between water clouds and bare soil. Finally, the nighttime 3.7 micron channel image has been widely used for detection and identification of nighttime stratus, especially when couple with the VIIRS IR imagery channel.

Figure 7. Differentiating between cirrus (ice) clouds and snow is greatly facilitated in the 3.7  $\mu\text{m}$  (albedo) band



**Figure A-7. Differentiating between cirrus (ice) clouds and snow is greatly facilitated in the 3.7  $\mu\text{m}$  (albedo) band.**

Figure A-7 shows an AVHRR scene where the 3.7 micron channel has been segregated into the albedo image to enhance the signatures of snow and cirrus clouds (Hutchison and Locke, 1997). Notice that the snow-covered Sierra Nevada Mountains, in the lower right corner of the scene, appear bright in the 645 nm imagery channel in the upper left panel. However, this same feature appear very dark in the derived 3.7 micron albedo image located in the in the lower right corner.



On the other hand, the several areas of water clouds, located to the left of a diagonal from the lower-right to the upper left corner, are unchanged in the scene. Finally, thin cirrus clouds, located to the right of this same diagonal, are enhanced in the 3.7 micron albedo image, if in comparison to the 12.0 micron image. Thus, the 3.7 micron image and the derived albedo image assist in identifying nighttime stratus and daytime water clouds, snow fields, and thin cirrus clouds fields.

#### A.4.2 VIIRS Imagery-Assist Channels

In accordance with the VIIRS SRD, non-imagery or imagery-assist channels can be collected at a lower resolution than imagery channels. Imagery-assist channels cannot be used to satisfy minimum system requirements but may be used to press toward satisfying objective level requirements. Raytheon has demonstrated the use of imagery-assist data with imagery for satisfying objective requirements for manually-generated cloud data products (Raytheon SFR, 1999). In this section, we present the phenomenology of some key imagery-assist channels and their application toward meeting VIIRS objective requirements. A more complete description will be provided in the post-PDR era.

##### A.4.2.1 The 1.61 Micron Imagery-Assist Channels (I3, M10)

The 1.6 micron band has long been advocated for distinguishing between snow and clouds in multispectral imagery (Valvoci, 1978). There are two VIIRS 1.6 micron bands, at moderate spatial resolution (M10) and at imagery resolution (I3). Figure A-8 shows the phenomenology in the SWIR spectral region.

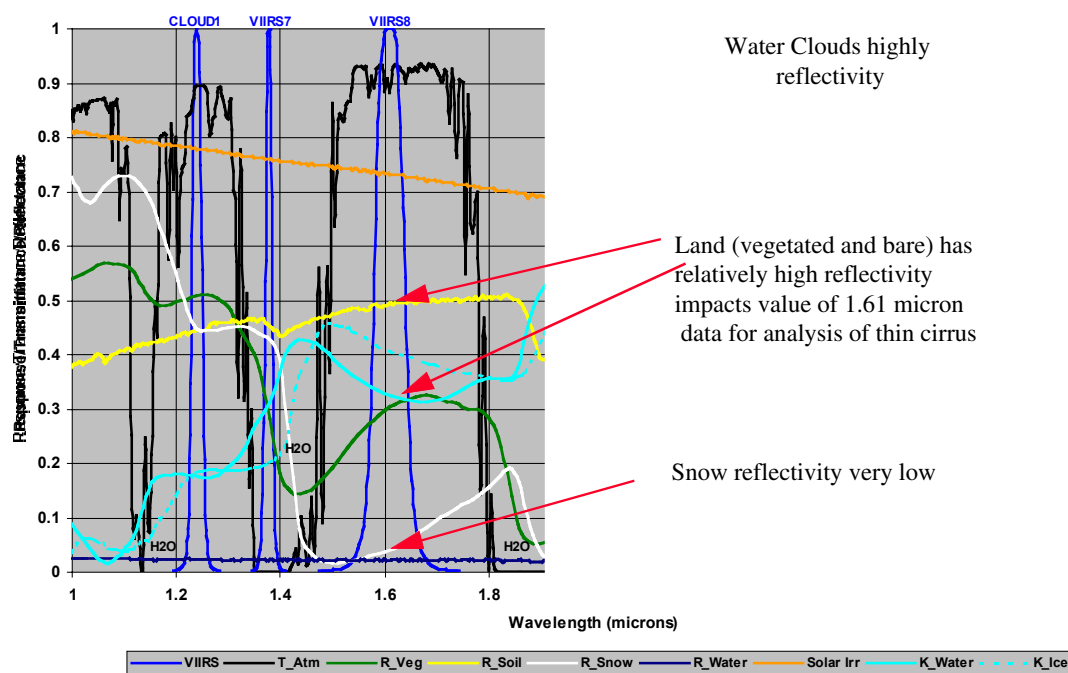
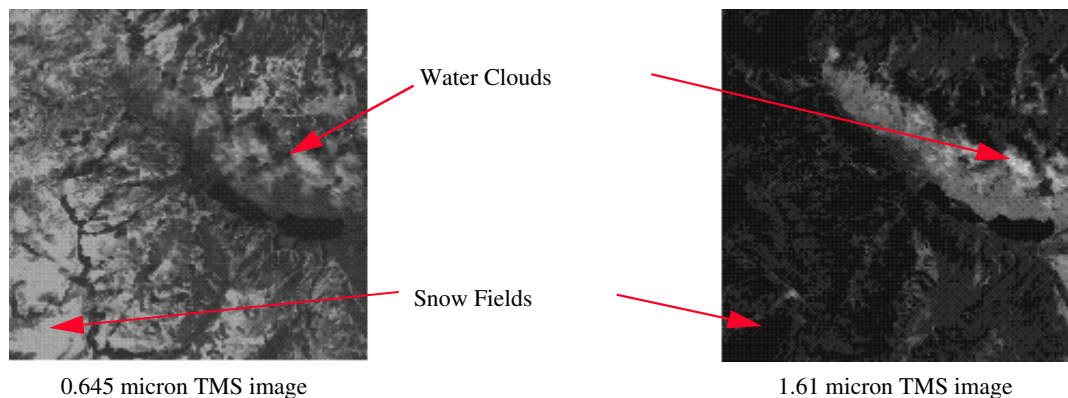


Figure A-8. Phenomenology of the 1.61 micron VIIRS Imagery-Assist Channels.

In the figure, the 1.6 micron band has its old designation (VIIRS8). The figure shows the reflectivity of ice dropping sharply at  $\sim 1.4$  microns and reaching a minimum near 1.5 microns before gradually increasing to another maximum at  $\sim 1.82$  microns. At the same time, the reflectivity of water clouds remains considerably higher making the band highly valuable for snow cloud discrimination. On the negative side, the reflectivity of both vegetative land and bare soil are both relatively high with the latter being significantly higher than the former. Thus, water clouds could become misclassified in this band, especially in sparsely vegetated regions. However, as previously noted, the thermal component of the 3.7 micron imagery channel is useful for avoid such misclassifications.

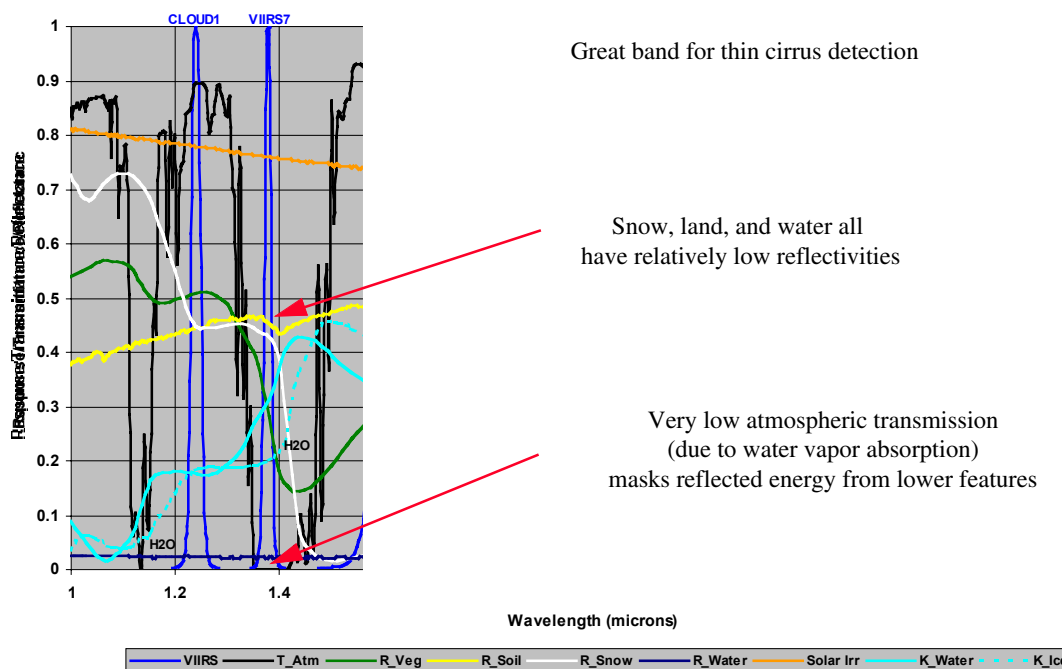
The phenomenology discussed in Figure A-8 is demonstrated in the LandSat Thematic Mapper Simulator scene shown in Figure A-9 which was collected via an aircraft flight over the Sierra Mountains. In the left panel is shown the 645 nm band while the 1.61 micron imagery is in the right panel. Notice that water clouds and snow fields are both highly reflective at the shorter wavelength. On the other hand, snow becomes very dark, indicative of its poor reflectivity, at the longer wavelength while water clouds remain highly reflective. Thus, discrimination between water clouds and snow fields becomes a trivial matter when both the 0.645 and 1.61 micron data are available.



**Figure A-9. Water clouds and snow appear similar in 0.645 micron band, but very different in the 1.61 micron channel.**

#### A.4.2.2 The 1.378 Micron Imagery-Assist Channel (M9)

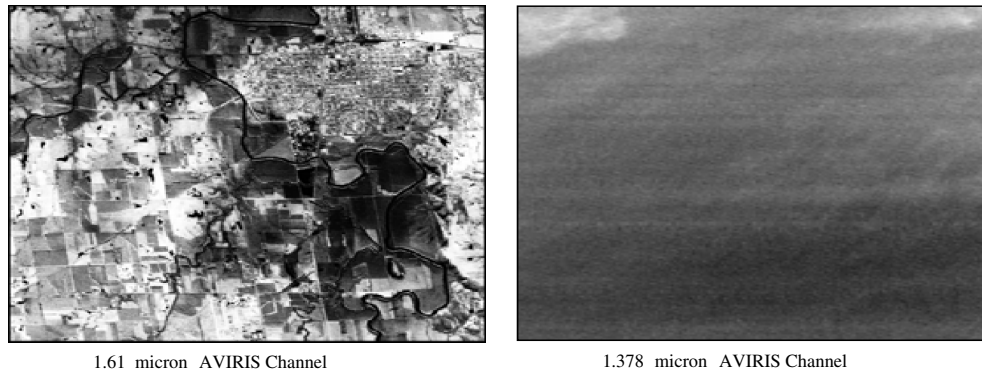
Data collected in the very narrow band centered on 1.378 microns has been shown to be most valuable for the detection of thin cirrus clouds in daytime imagery under most conditions (Gao et al., 1993; Hutchison and Choe, 1996). Figure A-10 shows the phenomenology in this spectral region.



**Figure A-10. Phenomenology of the 1.378 micron channel used for thin cirrus detection.**

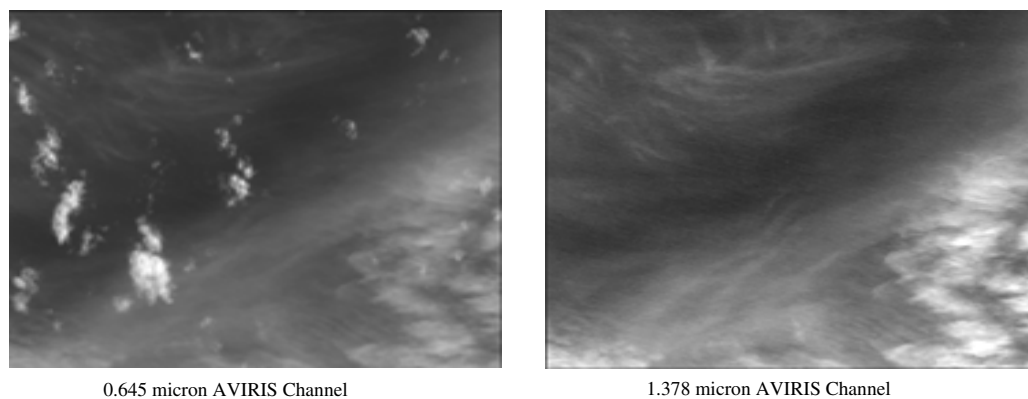
In the figure, the 1.378 micron band has its old designation (VIIRS7). The value of 1.378 micron data stems from the fact that most existing methods of identifying thin cirrus clouds rely upon imagery bands where water vapor and cirrus have similar spectral signatures which means that water vapor act as noise in the detection of thin cirrus clouds (Hutchison et al., 1995). On the other hand, water vapor strongly absorbs energy at 1.378 microns, as shown in Figure A-10, while most surface features, e.g. snow, bare soil, and vegetated land have about the same reflectivities. However, since water vapor density decreases exponentially with altitude in the atmosphere, reflected energy off of lower-level features will be totally absorbed under most circumstance. Thus, only middle level water clouds and higher level cirrus clouds, which occur above the moist layers of the atmosphere, reflect enough energy to be detected by space-based observing systems.

The phenomenology described in Figure A-10 is demonstrated in Figures A-11 and A-12. In the first case, data collected over Coffeyville, KS shows an apparently cloud-free day based upon the 1.61 micron imagery in the left panel. However, the 1.38 micron band in the right panel shows the scene is nearly completely overcast with thin cirrus. Lidar measurements made in conjunction with NASA's First ISCCP Regional Experiment (FIRE) confirmed the presence of the cirrus clouds.



**Figure A-11. Improved cirrus detection is also possible in the 1.378 micron channel over highly reflective (land) surfaces.**

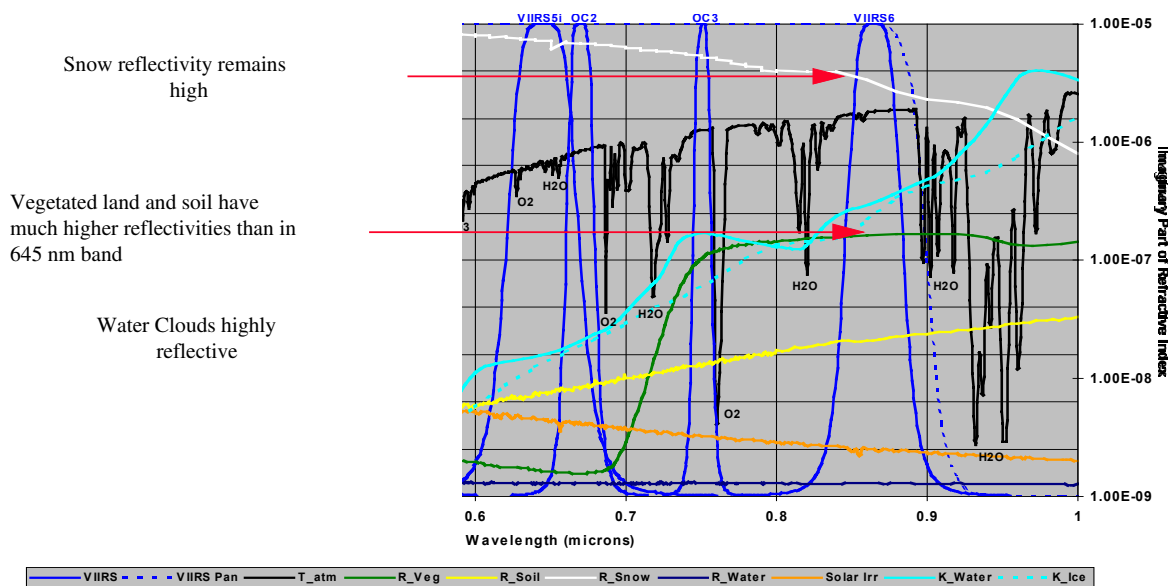
In Figure A-12, cirrus and lower-level water clouds appear in the 645 nm channel of Advanced Visible/InfraRed Imaging Spectrometer (AVIRIS) data collected over the Gulf of Mexico shown in the left panel. In the right panel the same scene is viewed in a 10 nm wide band centered at 1.375 microns. In this case, there is sufficient water vapor present in the atmosphere to absorb any solar energy which may have been reflected by the lower-level water clouds. Thus, only energy reflected off the cirrus clouds arrives at the detector.



**Figure A-12. Cirrus clouds are readily detected in the 1.378 micron channel, even in the presence of lower level water clouds.**

### A.4.2.3 The Near Infrared Imagery-Assist Channels (I2, M7)

There are two VIIRS .865 micron bands, at moderate spatial resolution (M7) and at imagery resolution (I2). Figure A-13 shows the phenomenology in the NIR spectral region.

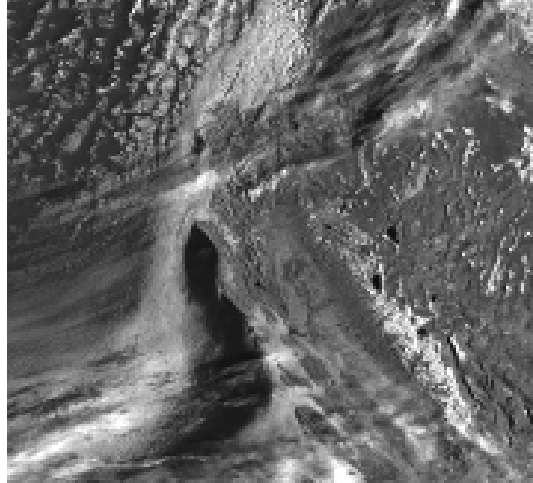


**Figure A-13. Phenomenology of the VIIRS NIR Imagery-Assist Channel (I2).**

In the figure, the 0.865 micron band has its old designation (VIIRS6). Data in this channel have been widely used with those in the 645 nm imagery band to create a vegetative index that measures the “greenness” of the Earth. The reasons are clearly shown in the figure. The reflectivity increases rapidly at wavelengths above 70 nm and becomes nearly constant between ~ 77 nm and 1.0 micron. On the other hand, the atmosphere has numerous water vapor absorption lines above 90 nm. The VIIRS NIR imagery assist bands are located in the region where atmospheric transmissivity is effected only slightly by atmospheric gases that have variable concentrations on a global scale. Therefore, highly accurate vegetative indices are expected.

The reflectivity of water remains very low in the 865 nm band which makes these data ideal for distinguishing between land and water boundaries. Meanwhile, the reflectivity of snow remains very high in this band when compared to the 645 nm imagery channel. Thus, the 865 nm channel has no value for snow cloud discrimination. Optimum snow cloud uses the 645 nm band along with the 1.61 and 3.7 micron data.

A comparison of Figure A-14 with Figure A-2 reveals the value of the 865 nm channel for land sea discrimination. Vegetated land and bare soil both are highly reflective in the larger wavelengths while the ocean is a poor reflector at the 865 nm wavelength. Thus, land-sea boundaries are very pronounced in the 865 nm image-assist band.



**Figure A-14. Signatures in AVHRR Channel 2.**

## A.5. REFERENCES

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Valovcin, F. R., 1978: Spectral radiance of snow and clouds in the near infrared spectral region, Technical Report AFGL-TR-78-0289, 46 pp., Air Force Geophysics Laboratory, Bedford, MA.

